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The flow of nutrients in a *Pinus merkusii* forest plantation in Central Java; the contribution of soil animals

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Abstract

The study of the contribution of soil animals to the flow of nutrients (SO_4^{2-}, NH_4^+, NO_3^-, Cl^-, K^+, Ca^{2+}, and Mg^{2+}) through soil columns was done in a *Pinus merkusii* (Jungh. & De Vriese) forest plantation at two altitudes (600 and 800 m a.s.l.) along an active stratovolcano, Mount Merapi, in Central Java. A field experiment using closed and open mesocosm systems was carried out in the wet season from October 1990 till April 1991. Litter percolate was collected using vacuum tube lysimeters. The results showed that the open systems, containing soil animals such as ants and earthworms, collected about 25-30% more percolate than the closed systems, in which these animals were absent. The dynamics of percolate volume and most of the nutrients showed more or less the same pattern in both plots except for SO_4^{2-}, Cl^-, and K^+ which originated from the volcano via rainfall. It seemed that the effects of macrofauna *i.e.* Araneae, Oniscoidea, Julidae, Formicidae, and Lumbricidae were evident for elements found in high amounts in the percolate, such as SO_4^{2-}, Cl^-, and K^+.

Keywords: Ants, earthworms, Indonesia, leaching, mesocosm, Mount Merapi, nutrient flow, *Pinus merkusii*, soil animals, tropical forest plantation, vacuum tube lysimetry.

Flux d'éléments nutritifs dans une plantation de Pinus merkusii *à Java-centre; contribution de la faune du sol.*

Résumé

L'étude de la contribution de la faune du sol au flux d'éléments nutritifs (SO_4^{2-}, NH_4^+, NO_3^-, Cl^-, K^+, Ca^{2+} et Mg^{2+}) a été réalisée à travers des colonnes de sol dans des plantations de *Pinus merkusii* (Jungh. & De Vriese) à deux altitudes (600 et 800 m) sur les flancs d'un stratovolcan, Mount Merapi, au centre de Java. Une expérimentation de terrain utilisant des mésocosmes fermés ou ouverts a été menée pendant la saison des pluies, d'octobre 1990 à avril 1991. Les percolats de litière ont été récoltés au moyen de lysimètres à dépression. Les résultats montrent que les systèmes ouverts contenant des groupes animaux tels que les fourmis ou les vers de terre permettent de recueillir environ 25 à 30% de percolat de plus que les systèmes fermés dépourvus de faune. Les dynamiques des volumes percolés et de la plupart des éléments nutritifs ont un comportement plus ou moins similaire aux deux altitudes, excepté pour SO_4^{2-}, Cl^- et K^+, d'origine volcanique et déposés par les pluies. Il semble que les effets de la macrofaune comme Araneae, Oniscoidea, Julidae, Formicidae et Lumbricidae, sont évidents pour les éléments trouvés en grandes quantités dans les percolats, comme SO_4^{2-}, Cl^- et K^+.

Mots-clés : Fourmis, vers de terre, Indonésie, lessivage, mésocosme, Mount Merapi, flux d'éléments nutritifs, *Pinus merkusii*, faune du sol, plantation forestière tropicale, lysimètre à dépression.

INTRODUCTION

Recently many authors have reviewed the role of soil animals in nutrient cycling (Verhoef and Brussaard, 1990; Wolters, 1991; Shaw *et al.*, 1991; Lee and Pankhurst, 1992; Roth, 1992). Available results are mainly based on laboratory studies with microcosms, while in the field the contribution of soil animals may be different. Odum (1989) criticized models on ecological succession based on microcosm studies in which respiration of the organisms is usually underestimated. Consequently, as resources such as space and nutrients become depleted in the closed systems, the rate of production becomes limited by the rate of decomposition and mobilization of nutrients.

As it is difficult to study the contribution of soil animals to the flow of nutrients under natural conditions, a mesocosm experiment using systems which are closed or open to soil animals is one alternative to study the role of soil fauna in the field. Teuben and Verhoef (1992) concluded that mesocosm experiments in combination with microcosm experiments are a good approach to study ecosystem processes.

The aim of this investigation is to study the contribution of soil animals to the flow of nutrients (SO_4, NH_4, NO_3, Cl, K, Ca, and Mg) through soil columns at different altitudes along an active volcano. Additionally, the volume and pH of the percolate was collected from the closed and open mesocosms.

MATERIALS AND METHODS

This study was conducted in a 32-year-old pine forest plantation (*Pinus merkusii* Jungh. & De Vriese) on the south-west slope of Mount Merapi (2911 m a.s.l.), Central Java. Two 2000 m^2 plots at altitudes 600 and 800 m a.s.l. were selected. Some characteristics of the study sites are described by Gunadi (1994); Gunadi and Verhoef (1994); Gunadi *et al.* (1994). The study was conducted during the wet season between October 1990 and April 1991.

The "mesocosm" is constructed of dark grey PVC, 13 cm diameter, 25 cm height, 0.5 cm thick, open at the top, and covered by 200 μm nylon gauze, with a closed bottom connected with a well closed dark glass bottle with a capacity of 225 mm. Soil water percolate was collected from the mesocosm by vacuum porous ceramic cup lysimeter. The tension inside the glass bottle was set at − 0.4 bar in order to suck the percolate. Therefore, a vacuum pump was used weekly (Gunadi *et al.*, 1994).

There were two types of mesocosms. In the open ones soil animals could enter and leave the mesocosm via 6 sideways holes, 3 cm diameter, in the upper part of the tube. Each hole was covered by 4 (for the 3 upper) and 2 mm nylon gauze (for the 3 lower holes); 3 holes on a level with the litter layer and 3 on a level with the fragmented layer. In the closed mesocosms there were no holes in the upper part of the tube. Principally, the macrofauna such as Araneae, Oniscoidea, Julidae, Formicidae, and Lumbricidae could not enter the closed mesocosms.

The mesocosm was filled using a soil core with an undisturbed soil column, including the litter and fragmented layers. Before installation all mesocosms were treated for one week at −5 °C to decimate the soil biota. Freezing (followed by thawing and drying) appears to be a successful method to eliminate microarthropods from coniferous soils (see Huhta *et al.*, 1989). All mesocosms were installed randomly below understorey vegetation with 8 replicates of open and closed mesocosms in each plot.

Every 1 or 2 weeks (depending on the intensity of the rainfall), the volume of percolate was determined and samples were taken for chemical analyses. During the whole period 15 series of percolate were collected. In the laboratory, the water samples were filtered through paper filters. A 80 ml subsample was acidified with HNO_3 to pH<2 for NH_4, K, Ca and Mg measurements. The remaining 20 ml subsample was used for NO_3, SO_4, and Cl measurements. Both were frozen at −5 °C until they were flown to The Netherlands for the analyses. Before measurements, the samples were stored in a dark room at 5 °C. SO_4, NH_4, NO_3 and Cl were measured using an autoanalyser (Skalar SA-40). K, Ca, and Mg were measured using a flame atomic absorption spectrophotometer (Perkin-Elmer 1100). Nutrient fluxes were estimated by multiplying the concentration by the volume and summing the result over the sampling period (7 months).

At the end of the experiment, all mesocosms were transported to the laboratory of Terrestrial Ecology, Salatiga, where the soils were carefully taken out. Berlese-Tullgren funnels were used for extracting the microarthropods. Macrofauna such as Araneae, Oniscoidea, Julidae, Formicidae, and Lumbricidae were collected using hand sorting.

Bartlett test for homogeneity of group variance was used, and the data that showed inhomogeneous variance were log-transformed before data analyses. A t-test was used to test the significance of the differences between annual means for percolate volume and animal abundance. Three-way ANOVA was used to compare the effects of 3 factors *i.e.* plot (2 levels: high and low plot), treatment (2 levels: closed and open mesocosm), and time (15 levels: series of 15 collections) on volume of percolate, pH and total elements output (SO_4, NH_4, NO_3, Cl, K, Ca, and Mg). Analyses were performed using computer software available in SYSTAT version 5.0.

RESULTS AND DISCUSSION

Soil animals present in closed and open mesocosms

In the closed systems 4 taxonomic groups of microarthropods were found in both plots at the

end of the experiment, *i.e.* Acarina, Hypogastruridae, Entomobryidae and Sminthuridae. In the open systems, besides these groups, macroarthropods (Araneae, Oniscoidea, Julidae, and Formicidae), Onychiuridae, and Lumbricidae were found in both plots (*table* 1). Apparently, the freezing treatment (of −5 °C) was not appropriate to eliminate all (stages of) microarthropods. Lower temperatures might have been more effective, but are considered to have greater side-effects on soil properties (see also Huhta *et al.*, 1989).

In the high plot the mean number of Hypogastruridae in the closed systems was higher than that in the open systems. In the low plot the mean number of Sminthuridae in the open system was higher than that in the closed system. Comparison between high and low plot was only possible for the open system for Araneae, Oniscoidea, Julidae, Onychiuridae, Formicidae, and Lumbricidae. Higher numbers of Lumbricidae were found in the high plot, while all other taxonomic groups had more or less the same density in both plots.

Volumes of percolates from the mesocosms

The mean volumes of percolates from closed and open systems differed significantly from each other in both plots (*fig.* 1, *table* 2); on the average, open systems collected about 25-30 % more percolate than closed systems. This may be caused by the burrowing activities of Formicidae and Lumbricidae.

It is well known that soil macrofauna, especially earthworms, can significantly modify porosity and pore size distribution which can influence soil physical properties such as aeration and water retention, infiltration, and drainage (Carter *et al.*, 1982; van de Westeringh, 1972; van Rhee, 1969). Earthworms such as *Lumbricus terrestris*, construct permanent, vertical burrows lined with faeces, which act as conduits that enhance drainage of free water. The faeces of earthworms are often preferentially enriched

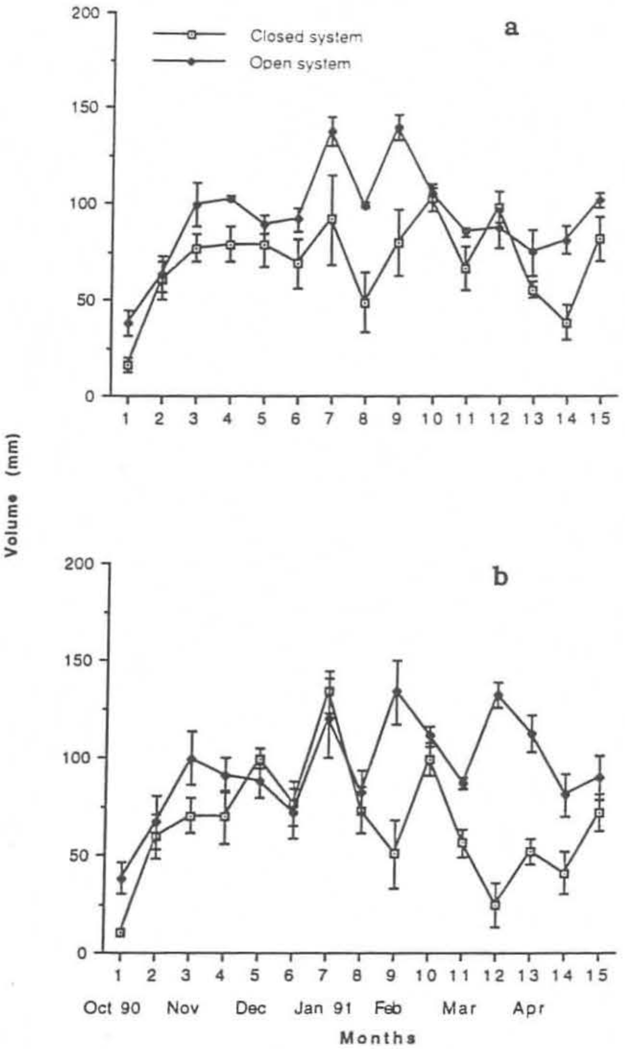

Figure 1. – Volumes of percolate ± S.E. collected from the mesocosms in the high (a) and low plots (b). The x axis is divided into 15 collections.

Table 1. – Mean numbers ± S.E. (n = 8) at the end of the experiment of the dominant soil animals. * = $p < 0.05$; N.S. = not significant; – = not present; when differences are significant the highest value is given in bold.

Taxonomic groups	High plot		Low plot	
	Closed system	Open system	Closed system	Open system
Acarina	12±2.8	19±2.9 N.S.	16±4.0	27±4.4 N.S.
Araneae	–	3±1.0	–	6±1.8 N.S.
Oniscoidea	–	2±0.3	–	1±0.2 N.S.
Julidae	–	2±0.8	–	3±1.8 N.S.
Onychiuridae	–	2±0.4	–	2±0.5 N.S.
Hypogastruridae	**82±14.0**	32±12.8 *	15±5.2	36±11.1 N.S.
Entomobryidae	8±1.4	10±3.2 N.S.	20±9.4	15±2.5 N.S.
Sminthuridae	56±15.2	22±8.4 N.S.	13±5.6	**17±2.8** *
Formicidae	–	37±30.6	–	8±5.3 N.S.
Lumbricidae	–	**4±1.1**	–	1±0.3 *

Table 2. – Mean, S.E. and F-values for the volume of percolate (mm) from the mesocosms n = 30; ** = p < 0.01 (t-test).

Description	High plot	Low plot
Closed system		
Mean volume (mm)	69.1	65.8
Standard error	5.9	7.9
Open system		
Mean volume (mm)	92.5	93.5
Standard error	6.5	6.6
F-values closed/open	7.161 **	7.291 **

in colloidal materials and usually have a high water-holding capacity (Mulongoy and Bedoret, 1989; Shaw *et al.*, 1991). Similar effects by ants have been reported by Wicken *et al.* (1976). These soil animals construct permanent structures as channel systems throughout the underground and aboveground nests which may have long-term effects on soil hydrology. It was reported by Lee and Pankhurst (1992) that one of the key functions of soil animals is increasing water infiltration and thus reducing soil loss by erosion.

We assume that colonization of soil animals of the open mesocosms, especially by Formicidae and

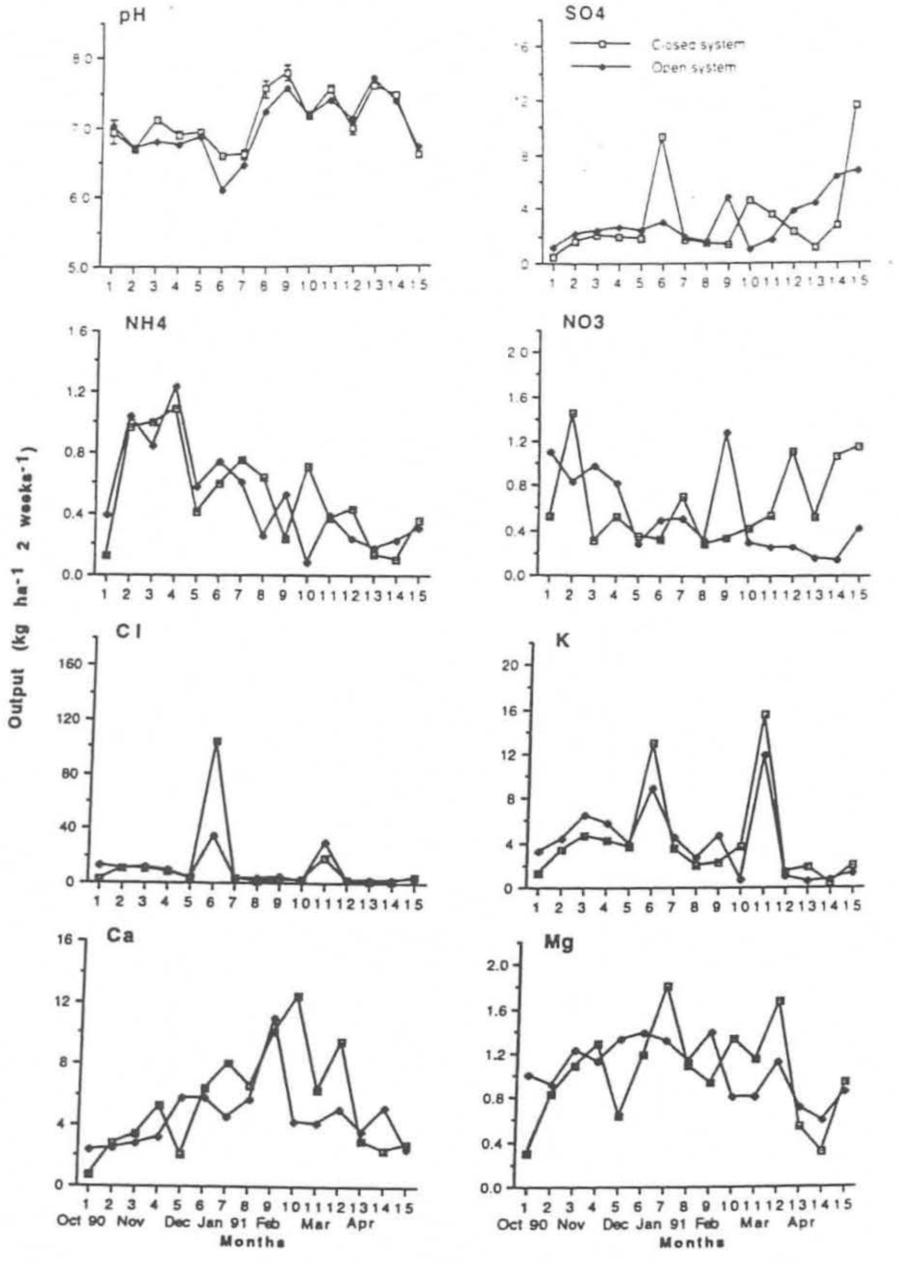

Figure 2. – pH and element output in percolates from the mesocosms in the high plot.

Table 3. – ANOVA results (F-values) for volume (mm), pH, SO_4, NH_4, NO_3, Cl, K, Ca, Mg (kg ha^{-1} 2 $weeks^{-1}$) against plot (2 levels: high and low plot), treatment (2 levels: closed and open mesocosms), and series (15 levels: 1st till 15th collections). n = 480; ** = p < 0.01; *** = p < 0.001; N.S. = not significant.

Sources	Volume	pH	SO_4	NH_4	NO_3	Cl	K	Ca	Mg
Plot	0.006 N.S.	3.769 N.S.	4.717 N.S.	0.635 N.S.	4.288 N.S.	1.941 N.S.	1.005 N.S.	1.696 N.S.	7.084 **
Treatment	73.390 ***	0.687 N.S.	10.823 N.S.	0.191 N.S.	0.742 N.S.	44.818 ***	12.214 ***	0.681 N.S.	1.914 N.S.
Time	15.967 ***	66.379 ***	12.444 ***	7.209 ***	1.909 N.S.	28.992 ***	27.785 ***	9.182 ***	8.813 ***
Plot*treat.	0.146 N.S.	7.169 **	7.471 *	0.012 N.S.	3.556 N.S.	0.389 N.S.	0.976 N.S.	1.104 N.S.	0.286 N.S.
Plot*time	0.578 N.S.	10.933 ***	3.567 ***	0.527 N.S.	0.854 N.S.	26.403 ***	5.410 ***	1.774 N.S.	1.269 N.S.
Treat.*time	2.275 **	1.420 N.S.	3.913 ***	0.711 N.S.	1.908 N.S.	3.708 ***	2.350 **	1.434 N.S.	1.735 N.S.
Plot*treat.*time	2.209 **	2.017 N.S.	2.918 ***	0.680 N.S.	1.089 N.S.	1.784 N.S.	1.128 N.S.	2.195 **	1.906 N.S.

Lumbricidae, takes some time; this we call an adaptive period. *Figure* 1 shows that in both plots the first month of study (October 1990) is the adaptive period, as during that time the volumes of percolate were the same for both closed and open systems. After that the volumes of percolate from the open systems were higher than from the closed systems. In the second half of February and March 1991, the volumes of percolate from both systems were the same. This might be caused by the heavy rainfall before those periods (about 300 mm per month) (Gunadi *et al.*, 1994), causing saturation of the mesocosms and decreasing the contribution of the soil animals in the open systems via destruction of the nests and burrows. From the middle of March 1991 till the end of this study, again open systems collected more water than closed systems. In the low plot, the adaptive period seems to run from October until the middle of January. This might also be caused by heavy rainfall (about 300 mm per month) during that period. From the middle of January until the end of this study, open systems collected more percolate in the low plot.

Dynamics of the flow of nutrients

Table 3 shows ANOVA results of all variables against three factors *i.e.* plot (high and low plot), treatment (closed and open systems) and time. The dynamics of pH and nutrient output in percolate from closed and open mesocosms in the high and low plot are shown in *figures* 2 and 3. Volume, Cl and K differed significantly in closed and open systems.

The effect of treatment on pH of percolate and output of SO_4 was different in the high and low plot. The dynamics of the volume of percolate and output of K, SO_4 and Cl during this study were different in the closed and open systems. The plot* time interactions are significant only for elements which are usually found in high amounts such as SO_4, Cl and K.

The dynamics of the volume of percolate (*fig.* 1) and output of Ca and SO_4 (*fig.* 2 and 3) during this study were different in the closed and open systems in the high and low plots.

Compared with the dynamics of the volume of percolate in the closed and open systems in both plots which has been explained before, the dynamics of the output of SO_4 and Ca are difficult to explain because closed systems collect sometimes more and sometimes less SO_4 and Ca than open systems. According to Gunadi *et al.* (1994), SO_4 fluctuations in percolate from the open mesocosms had a close relation to the volcanic input via rainfall and throughfall. The contribution of soil animals, however, to the SO_4 availability is not clear. Ca output in the percolate was much higher than in the throughfall (Gunadi and Verhoef, 1994). The fluctuations of the output of Ca from closed and open systems are difficult to explain. E.g. in the closed systems there were microarthropods (*i.e.* Acarina, Hypogastruridae, Entomobryidae and Sminthuridae), which can contribute to Ca mobilization. In open systems, apart from the microarthropods above, we found macrofauna such as Oniscoidea, Julidae and Lumbricidae which also can contribute to Ca mobilization. Collembola (Seastedt and Crossley, 1983) as well as isopods (Reyes and Tiedje, 1976) can digest Ca oxalate by means of mineralization by bacteria living in their guts, resulting in a higher Ca availability in the faeces (Teuben and Verhoef, 1992). Ca output was sometimes lower in the open systems than in the closed systems. This can partly be explained by the fact that some macroarthropods such as Oniscoidea and Julidae immobilize Ca carbonate to calcify their exoskeleton (Hopkin and Read, 1992; Sutton, 1972, Verhoef, 1994). It can be concluded that

Table 4. – Total elements output (kg ha^{-1} 7 $months^{-1}$) in percolates from the mesocosms.

Element	High plot		Low plot	
	Closed system	Open system	Closed system	Open system
SO_4-S	42.9	45.9	43.1	68.2
NH_4-N	7.9	7.6	6.3	7.4
NO_3-N	9.6	8.2	9.9	12.3
Cl	174.5	134.0	225.9	148.1
K	62.6	60.6	47.0	78.6
Ca	81.3	67.9	63.3	68.1
Mg	15.0	15.7	12.3	13.6

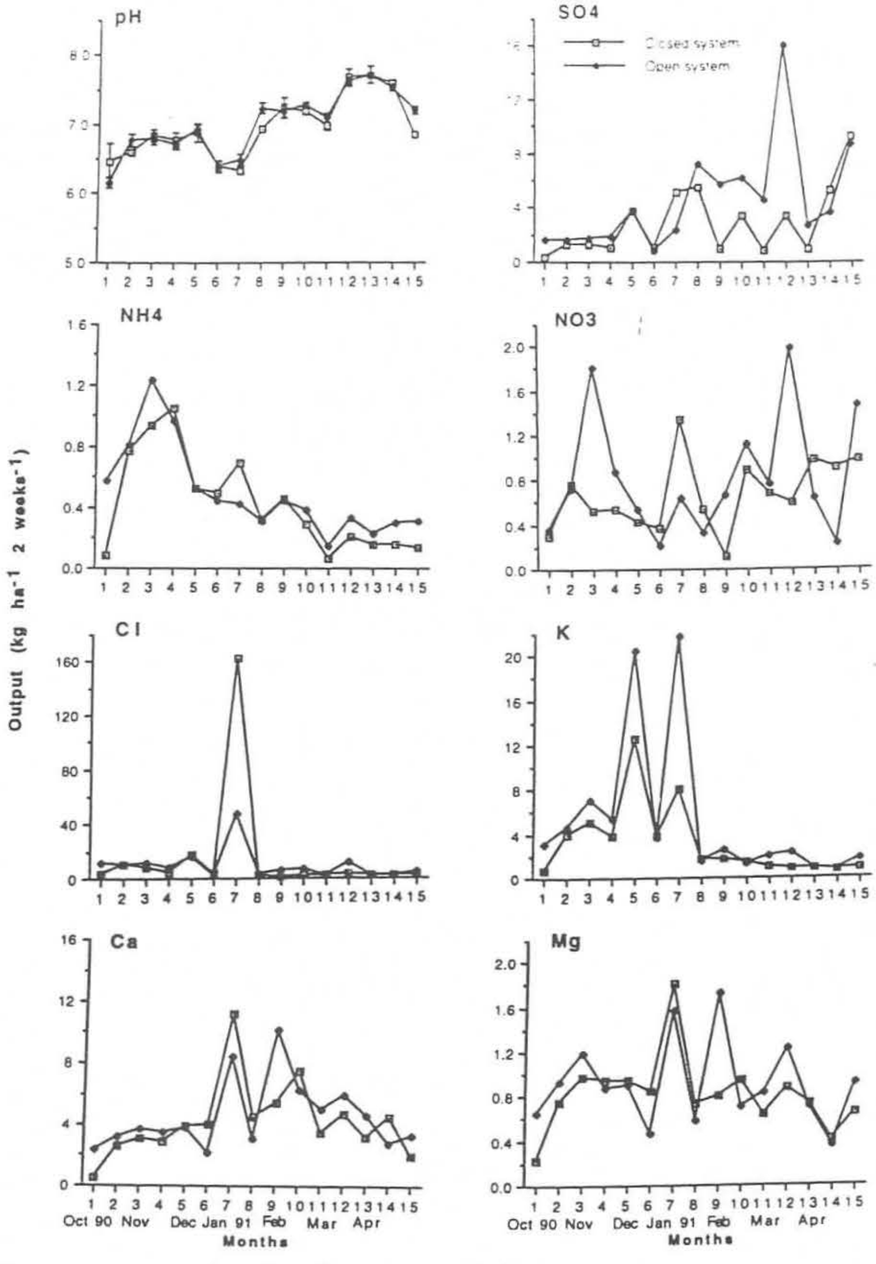

Figure 3. – pH and element output in percolates from the mesocosms in the low plot.

nutrient dynamics could not fully be explained in this investigation.

Total element outputs

In the high plot, most of the element outputs were similar between closed and open systems, except for Cl, which was higher in the closed systems (*table* 4). For the low plot, most of element outputs were also similar in closed and open systems, except for SO_4 and K, which were lower in the closed systems. As in the high plot, the total output of Cl in the low plot in the closed systems was higher than that in the open systems.

It was reported by Gunadi *et al.* (1994) that the input of nutrients via rainfall and throughfall in the study sites, especially that of SO_4, Cl and K, was very high compared to other data from tropical pine forest plantations. So it seems that effects of macrofauna are only evident for those elements which are found in high amounts in the percolate. The mechanisms, however, are not clear at the moment.

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